HTML ABSTRACT + LINKS

Real Time Read-Out of Single Photon Absorption by a Field Effect Transistor with a Layer of Quantum Dots

B. Kardynał[a], A. J. Shields[a], N. S. Beattie[a,b], I. Farrer[b], D. A. Ritchie[b]

[a]*Cambridge Research Laboratory, Toshiba Research Europe Ltd, Cambridge, CB4 3HS, UK*
[b]*Cavendish Laboratory, University of Cambridge, Cambridge, CB3 0HE, UK*

Abstract. We present results of photon counting with a single photon detector based on field effect transistor with a layer of quantum dots in close proximity to the channel. Detection of a photon is achieved when photo-hole is captured by negatively charged InAs dot leading to a step-like increase of the current in the channel of the transistor. We use a transimpedance amplifier with a cryogenic stage and ac coupling on the input to convert the current steps of 1-2 nA height into voltage peaks with microsecond time resolution. We show that single photon counting with 0.3% efficiency, dark count rate below 10^{-8} ns^{-1} is then achieved, while the jitter limited by the circuit can be as low as 8.5 ns.

INTRODUCTION

Operation of many devices, such as optical memories [1], lasers [2] or infra-red detectors [3], relies on the charge storage in InAs dots. It was also shown that AlGaAs/GaAs high electron mobility transistor with a layer of quantum dots in close proximity of the electron channel can be used to detect single photons [4]. In this paper we demonstrate photon counting with sub-microsecond response times with such quantum dot field effect transistor (QDFET) using a custom amplifier with a cryogenic input stage [5]. We show the QDFET/amplifier combination to have a low dark count rate and jitter limited by the capacitances of the circuit.

EXPERIMENTAL RESULTS

In a quantum dot QDFET the source-drain conduction in the quantum well occurs through hopping in a disordered potential created by highly charged dots in the vicinity of the channel. In devices in which the active region contains just a few hundred quantum dots and whose dimensions are comparable to the hopping length, the interactions between the electrons stored in the dots and electrons in the channel are strong enough to result in a small increase in the source-drain current when a photo-generated hole recombines with an electron trapped in a dot [4].

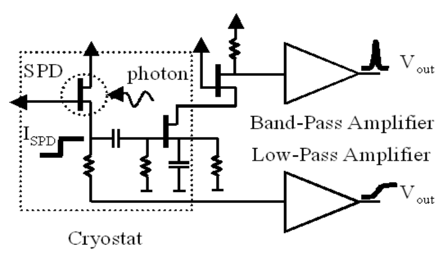

FIGURE 1. Schematic diagram of the amplifier used for photon counting.

In order to use QDFET for photon counting steps in the source-drain current need to be converted into voltage peaks. This has been achieved using the amplifier shown in Figure 1, which consists of a cascode pre-amplifier followed by a band-pass amplifier [5]. The input transistor of the cascode could be placed very near the QDFET, which is operated at 4.2 K, thereby reducing the effect of the lead capacitance between the cryogenic and room temperature parts of the circuit. This allows radio frequency operation of the detector, even though it has a channel resistance in excess of 100 kΩ. Signal from the detector is ac coupled to the input of the amplifier.

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The signal on the output of the cascode is passed to a band-pass amplifier, which serves to shape the output pulse and to reduce the noise. Reset pulse necessary for refilling the dots with electrons after illumination [4] was sent based on the measurements of total current of the detector with a low-pass amplifier.

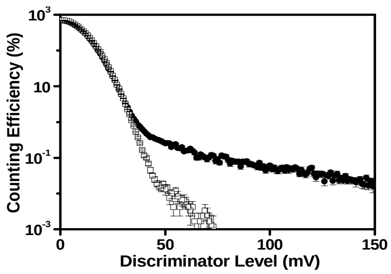

FIGURE 2. Counting efficiency of the single photon (●) and dark counts (□) as a function of the discriminator level.

The device studied here is modulation doped GaAs/AsGaAs quantum well heretostructure, which had a dot density of 1.4 10^{14} m^{-2}, separated from the 20 nm thick GaAs channel by a 10 nm thick AlGaAs barrier. The wafer was processed into a transistor with 1 µm wide mesa between a source and drain and gated with 1 µm long NiCr semitransparent gate. The active area of the device is defined by the overlap of the mesa and the gate. The QDFET was biased with 20 mV across the source-drain and -0.6 V between the gate and drain. Each detection cycle was initialized by a 1.4 V and 1 µs reset gate pulse. The detector was illuminated with pulses from a laser diode emitting light at 684 nm, with the laser clock of 400 kHz. Each pulse had on average of 0.1 photons per 1 µm^2 (area of the detector).

Figure 2 shows results of photon counting as a function of discriminator level. Each measurement was performed for 500 ns starting with the arrival of the laser pulse to count photons and simultaneously 1 µs later to measure the dark counts. For a given discriminator level a count is added whenever the rising edge of the peak from the output of the detector circuit crossed the value of the discriminator level.

Maximum efficiency of the device of 0.3% is obtained when the dark count rate is 0.015% at 50 mV discriminator level. Measured efficiency of the device is limited by reflection from the gate and low absorption in GaAs well and corresponds to 21% of photons absorbed in the well being detected.

The main source of the dark counts in the system at low discriminator levels (below 47 mV) is the amplifier noise. Second contribution is caused by random telegraph signal in the detector itself and it can be very small depending on the gate voltage. [5]. It drops abruptly with the discriminator level in Figure 2 and when it dropped below resolution (10^{-8} ns^{-1}, at 83 mV), the photon counting efficiency is still 0.09.

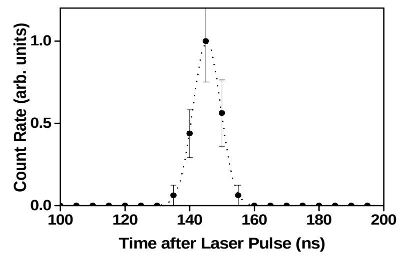

FIGURE 3. Time resolved single photon counting (■). Dotted line shows Gaussian fit to the data.

The jitter of the detection was estimated in time resolved counting (Figure 3), when counting was performed in 5 ns windows starting at different times after the laser pulse, at 150 mV discriminator level. When fastest amplifier was used all the counts occur within 20 ns. A Gaussian fit to the data estimates the full width at half height of the peak to 8.5 ns. This value is limited by the capacitance of the circuit.

SUMMARY

In this paper we present result of photon counting with quantum dot field effect transistor. Conversion and amplification of the single photon signal from the detector using an amplifier with cryogenic input stage allows counting with maximum efficiency of 0.3% and efficiency of 0.09% when dark count rate drops below 10^{-8} ns^{-1} and with jitter of 8.5 ns. Both the dark count rate and the jitter are limited by the amplifier.

REFERENCES

1. G. Yusa and H.Sakaki, Appl. Phys. Lett. **70,** 345 (1997).
2. D. Bimberg, M. Grundmann, N. N. Ledentsov in “Photonic Devices” in *Quantum Dot Heterostructures*, John Wiley and Sons, 1999, pp.279-302.
3. J. Phillips, K. Kamath and P. Bhattacharya, Appl. Phys. Lett. **72**, 2020 (1998).
4. A. J. Shields, M. P. O'Sullivan, I. Farrer, D. A. Ritchie, R. A. Hogg, M. L. Leadbeater, C. E. Norman, and M. Pepper, Appl. Phys. Lett. **76**, 3673 (2000).
5. B. E. Kardynał and A. J. Shields, N. S. Beattie, I. Farrer, K. Cooper and D. A. Ritchie, Appl. Phys. Lett. **84**, 419 (2004).

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